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X-ray afterglows and spectroscopy of Gamma-Ray Bursts

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Abstract. I will review the constraints set by X-ray measurements of afterglows on several issues of GRB, with particular regard to the fireball model, the environment, the progenitor and dark GRB.

1. Introduction

This conference took place few months after the switch-off of BeppoSAX (Piro, Scarsi & Butler 1995), on April 30, 2002. Launched on April 30, 1996, this mission carried out observations of all classes of X-ray sources during its operative lifetime of 6 years. A total of 62 Msec of pointed observations with its Narrow Field Instruments (NFI) were carried out. A substantial fraction (about 50%) of the total observing programme was devoted to observations of compact galactic sources and AGN, i.e. the classes of sources mostly suited to the exploitation of the broad band spectral coverage of BeppoSAX NFI (0.1-200 keV).

The other strong asset of the mission was the capability of discover and carry out deep observations of transient phenomena in the sky. This was assured by wide field X-ray and gamma-ray monitors (Wide Field Cameras, WFC, and Gamma-Ray Burst Monitor, GRBM) coupled with a high level of flexibility of ground scientific operations in carrying out fast Target of Opportunity Observations (TOO) with NFI. In fact, a substantial part of the program was devoted to such observations: about 190 NFI observations (corresponding to a total of 7.2 Msec), out of which 2.2 Msec on Gamma-Ray Bursts. Turning then to GRB, 56 GRB (including 8 X-ray rich GRB) were localized by wide field instruments and their position distributed within few hours. 38 GRB were observed with fast TOO observations (from 5 hrs to 1 day) with NFI. The first GRB observation took place on July 20, 1996, during the scientific verification phase (Piro *et al.* 1997), and the last one just the last days of operations. The most famous events were GRB970228, that led to the discovery of the first X-ray and optical afterglows (Costa *et al.* 1997, van Paradijs *et al.* 1997), GRB970508 whose precise and fast localization (Piro *et al.* 1998) allowed the first determination of distance and the discovery of the first radio afterglow and fireball observational evidence (Metzger *et al.* 1997, Frail *et al.* 1997), and GRB980425 (Pian *et al.* 2000), with its association with SN1998bw (Galama *et al.* 1998).

In recent years, most of the research activities in the field have focussed on 3 main topics.

- Progenitor and central engine.

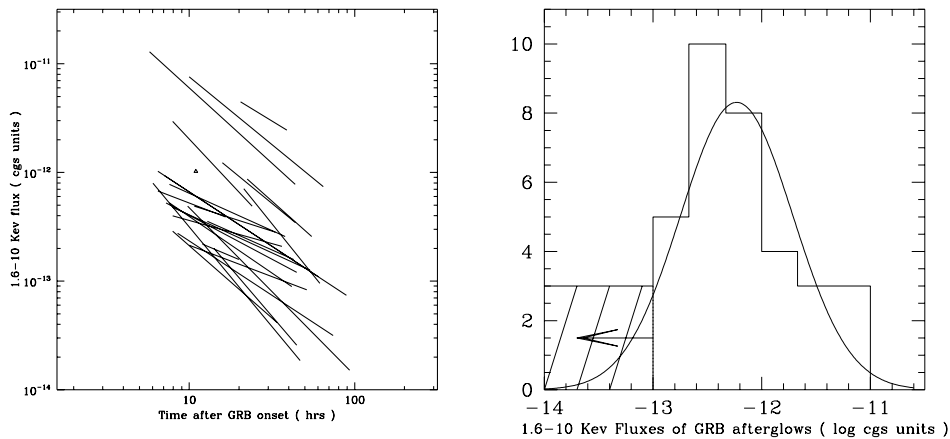


Figure 1. Light curves (best fit power laws: left panel) and distribution of $F(1.6-10 \text{ keV})$ at 11 hrs (right panel) with BeppoSAX

- Origin of dark GRB, X-ray flashes and short GRB
- Cosmology with GRB

Those areas of research are closely intertwined. The origin of dark GRB or X-ray flashes could have relevant implications both on the progenitor/central engine and on cosmological studies. The nature of the progenitor is then relevant to cosmological studies with GRB, because of their possible use as tracers of star-formation in the Universe. In this review I will focus on the impact of X-ray measurements on the fireball model, the environment and the origin of the progenitor, and on dark GRB.

2. The catalogue of BeppoSAX afterglow observations

BeppoSAX has performed 39 follow-up observations of GRB, 38 following localizations by BeppoSAX wide field instruments, and one (GRB000926) from an external trigger. We have considered here 36 observations, excluding the cases of GRB960720 (the first localization of a GRB by BeppoSAX when the TOO was performed one month after the burst), GRB990705 (due to a contamination from off-axis strong source), and GRB980425 (=Sn1998bw). Results from a subset on this sample (31 GRB) have been published in De Pasquale et al.(2003). The observations started typically 8 hours after the burst (ranging from 5 hours to 1 day), usually with a second observation taken 1-2 days after the burst. The sample is constituted primarily by events triggered by the gamma-ray burst monitor, but includes also all the X-ray rich GRB and X-ray flashes triggered (in real time) by the X-ray Wide Field Cameras. All events were long GRB, with the shortest lasting about 2 seconds.

The first result of the analysis is that the X-ray afterglow is a common feature in GRB. Only in three cases we do not find any source in the WFC error box (with an upper limit around $10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$), while in three other events

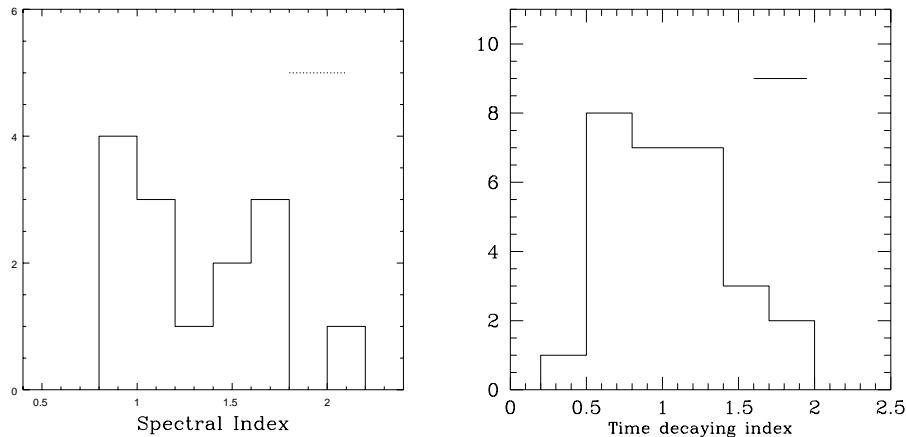


Figure 2. Distribution of spectral and temporal indices of afterglows observed with BeppoSAX

a source is detected but with no significant fading behaviour. Therefore X-ray afterglows are present in $\gtrsim 83 - 92\%$ of the GRB. We will come back to this result in the context of dark GRB in a following section.

3. Implications on the fireball model and jet scenario

We have characterized the temporal and spectral behaviour of the afterglows with a power law model, including the absorption by our Galaxy and at the source, as follows: $F(t, E) = F_0 \exp(-\sigma N_H) t^{-\delta} E^{-\alpha}$, where α is the energy spectral index. In Fig.1 (left panel) we show a collection of power law decay for afterglows in our sample.

We find, confirming the result reported in Piran et al. (2001), – that was based on a more limited sample of events –, that the distribution of afterglow fluxes observed at 11 hours is very narrow (Fig.1, right panel). As argued by Piran et al., this result implies that the kinetic energy of the fireball in all GRB of this sample is also very narrowly distributed, independently supporting the result by Frail et al. (2001) of a universal energy reservoir on GRB. We note, however, that the analysis of Piran et al provides only the width of the distribution, and not the absolute value of the energy.

Now we focus on the distribution of temporal and spectral indices and the implications on the fireball model. We find that both indices distribution are narrow, clustering around the average values $\alpha = 1.13 \pm 0.07$ and $\delta = 1.2 \pm 0.1$ (Fig.2). The determination of these values allows a comparison with the expectation from different realization of the fireball model, in which the two indices are related each other through the so called closure relations (Sari, Piran & Halpern 1999, Chevalier & Li 1999). We consider fireball expansion in a constant density medium (ISM) or in a wind-like medium, with a density profile following r^{-2} (wind) both for a spherical and a collimated (jet) flow. The results are summarized in table.1, where the closure parameter C (that has to

be consistent with 0) is given for these different cases. The following conclusion are derived for the average properties of the fireball in the time frame from few hours to 1-2 days.

- The X-ray emission is generated from electrons in the cooling regime (i.e. the cooling frequency ν_c is below the X-ray range)
- The index of the electron distribution is $p = 2.26 \pm 0.14$
- The fireball expansion for $t \lesssim 2$ days is consistent with spherical outflow, either in ISM or wind. This allows us to set a lower limit to the collimation angle of the jet: $\theta > 11^\circ (n/E_{iso,52})^{1/8} (t/2days)^{3/8}$ (vs the average of 6° from Frail et al. 2001)

Table 1. Constraints on the fireball model from X-ray afterglows

Regime	ISM	Jet	Wind
$\nu < \nu_c$	$C = \delta - \frac{3}{2}\alpha$	$C = \delta - 2\alpha - 1$	$C = \delta - \frac{3}{2}\alpha - \frac{1}{2}$
$\alpha = \frac{p-1}{2}$	$C = -0.49 \pm 0.14$	$C = -2.03 \pm 0.17$	$C = -1.0 \pm 0.14$
$\nu > \nu_c$	$C = \delta - \frac{3}{2}\alpha + \frac{1}{2}$	$C = \delta - 2\alpha$	$C = \delta - \frac{3}{2}\alpha + \frac{1}{2}$
$\alpha = \frac{p}{2}$	$C = 0.0 \pm 0.14$	$C = -1.0 \pm 0.17$	$C = 0.0 \pm 0.14$

4. Broad and narrow X-ray features: environment and progenitors

The GRB and its afterglow are very well explained by the fireball model, in which a highly relativistic outflow from the central source produces the observed emission. On the other hand, this process essentially loses "memory" of the central source: the shocks that are thought to produce GRB and afterglow photons take place over a distance scale that is about 10 orders of magnitude greater than the size of the central source. In addition, this is almost independent of the details of the central source, depending primarily on basic parameters as the total energy, the collimation angle of the outflow (jet), the fraction of energy in relativistic electrons and magnetic fields and the density of the external medium.

A very effective method to gather information about the progenitor is to study line features produced in the environment of the GRB. The iron line is an ubiquitous feature in all families of X-ray sources (Piro 1993). Most of the searches of features in GRB have been therefore concentrated at the energies of this element, i.e. (at rest frame) 6.4 to 6.9 keV for K_α lines from neutral to H-like ions, 9.3 keV for the recombination edge in emission from H-like ions and 7.1 keV, the energy of the absorption edge from neutral iron in absorption. So far there are 6 independent measurements of iron features from 4 different satellites (see Piro (2003) and references therein plus the recent case of GRB010220 (Watson *et al.* 2002)). While each single measurement is not of overwhelming statistical significance, the overall scenario is rather compelling. There are so far four burst with an independent redshift measurement from optical spectra. In three of these events the emission features detected in the afterglow phase are consistent with

highly ionized iron, while in one case there is evidence of a transient absorption edge during the main GRB pulse (Amati *et al.* 2000).

In the *distant reprocessor scenario* the line-emitting medium is external to the fireball region, as suggested by the presence of the absorption edge. In the early phase of the burst this medium is still to be completely ionized by the GRB photons, thus producing an absorption edge from neutral iron. As the ionization front reaches out the external border of the medium, this becomes completely ionized (Perna & Loeb 1998, Boettcher *et al.* 1999), thus explaining the disappearance of the absorption edge. On a time scale given by the recombination time, electrons start to recombine on ionized iron, thus producing the emission line and recombination edge observed in the afterglow phase. In an alternative model (Mészáros & Rees 2001), it is assumed that the central source, after the event producing the GRB, continues its activity - at lower power -, heating and ionizing a close-by line emitting medium (*local reprocessor scenario*). The progenitor is likely a massive star that undergoes a core-collapse supernova explosion (collapsar: Woosley 2001). In the distant reprocessor scenario, this explosion takes place about a month before the event leading to the GRB (Vietri & Stella 1999), and are the Supernova ejecta illuminated by X-ray photons of the gamma-ray burst that produce the lines. This is also consistent with the line width observed in GRB991216 (Piro *et al.* 2000), that corresponds to an outflow velocity of 10% of the speed of light, as typically observed in Supernovae. In the local reprocessor scenario the two events are almost simultaneous. In addition to Fe features, recent detections of soft X-ray lines by ionized elements as S, Si, Mg (Reeves *et al.* 2002) supports the association of GRB with SN-like explosions. In particular, those lines are blue-shifted with respect to the rest-frame energies by about 10% of the speed of light.

A point to be noted regards the origin of iron in the two scenarios. In the case of distant reprocessor, a large mass of iron is required, $\approx 0.05M_{\odot}$. This is consistent with the mass of iron group elements ejected in SN explosion. Because iron is actually the end result of the decay chain Co56(6.1 days)-Ni56(78.8 days)-Fe56 decay, a minimum delay between the SN explosion and the GRB of 2 months is required. In the case of the local reprocessor scenario, a modest amount of iron ($< 10^{-8}M_{\odot}$) suffices. In the framework of the collapsar model this material is advected from the iron core when the jet and its associated cocoon propagate around the rotation axis of the star and break out at the surface of the star. The energy in the cocoon ($\approx 10^{51}erg$) could be released in few hours after the burst and be the source of ionization and heating of the line-emitting material.

5. X-ray absorbers and environment

The spectra of X-ray afterglows show, in several cases, an intrinsic absorption in the range $10^{21-22}cm^{-2}$ (De Pasquale *et al.* 2003, Stratta *et al.* 2003). This is consistent with the column density measured in star-forming Giant Molecular Clouds in our Galaxy (Solomon *et al.* 1987), strengthening the connection of GRB with star formation sites.

Absorption data in the prompt phase are still very sparse. There are a few GRB with an absorption column density $N_H \gtrsim 10^{23}cm^{-2}$ (e.g. Frontera

et al. 2000, in' t Zand *et al.* 2001, Guidorzi *et al.* 2003). On the contrary, the column density measured in the afterglow phase *in the same burst* is one order of magnitude less. This behaviour is expected if the absorbing medium with a density typical of a GMC ($n \approx 10^2 - 10^5 \text{ cm}^{-3}$) is indeed lying within a few parsec from the GRB. In such a case it will be ionized by the GRB photons, becoming effectively transparent in the afterglow phase (Lazzati, Perna & Ghisellini 2002). Piro *et al.* (2002) have noticed that the absorber spectrum in the afterglow of GRB000210 is consistent with a medium in a low ionization stage, suggesting the possibility that the absorber is actually condensed in high-density ($n \approx 10^9 \text{ cm}^{-3}$) clouds. The large column density in the prompt phase could then be explained by the very small fireball region visible to the observer being fully covered by a single cloud. As the visible region of the fireball increases, it will become *partially covered* by the cloud ensemble, producing again a reduction in the effective column density. This scenario can also account for the erratic variations of the column density reported during the prompt phase of GRB010222 (in' t Zand *et al.* 2001). Clearly, high quality spectra are needed to progress beyond the simple uniform absorber model that is fitting the present data, allowing detailed test of partially covered and photoionized absorbers.

6. The X-ray view of dark GRB

One of the most intriguing issues on recent research of GRB regards the origin of the so-called dark GRB. We have mentioned above that about 90% of the GRB do show an X-ray afterglow. On the contrary, only about 40% of them have an optical afterglow (De Pasquale *et al.* 2003). There has been considerable discussions on whether this effect is due to an observational bias or not. The first point to be stressed is that the optical upper limits on these events lie on average two magnitudes below the average magnitudes measured for events with optical transients (OTGRB) (Lazzati, Covino & Ghisellini 2002). However, the detection of a few optical transients with magnitudes below some of the upper limits on dark GRB (e.g. Berger *et al.* 2002) suggests that some of the dark GRB are indeed a faint end extension of OTGRB, rather than a separate class of events.

Apart from semantic consideration, the origin of this behaviour would still be not-trivial. For example, it could be due to an intrinsic property (underluminous events), a distance effect (but at $z \lesssim 5$, since for higher redshift the optical should be almost completely absorbed, see below) or a fast decay, as that expected for a highly collimated jet. *In all these cases the afterglow flux should scale of the same factor at all wavelengths.*

On the contrary, the optical flux of a GRB at $z \gtrsim 5$ or of a GRB in a dusty star forming region should be depleted not only in absolute magnitude but also with respect to other wavelengths. We have therefore carried out a study of dark GRB vs OTGRB comparing their X-ray vs optical fluxes (see also De Pasquale *et al.*, this conference). The results can be summarized as follows.

- The X-ray flux of afterglows of dark GRB's is on average a factor of 6 lower than that of OTGRB.

- In 75% of dark GRB's, the upper limits on the optical-to-X-ray flux ratio (f_{OX}) are consistent with the ratio observed in OTGRB. This population of events is therefore consistent with being OTGRB going undetected in the optical because searches were not fast or deep enough.
- However, for about 25% of dark GRB, f_{OX} is at least a factor 5-10 lower than the average value observed in OTGRB, and also lower than the smallest observed f_{OX} . Furthermore, the optical upper limits on these events are also lower than the faintest optical afterglow. These GRB cannot be therefore explained as dim OTGRB's, and we refer to them as *truly dark or optically depleted GRB*.

We stress that the upper limit on f_{OX} for optically depleted GRB is model-independent, being derived by a comparison with the optically bright GRB, where the f_{OX} distribution is rather narrow, clustering around the average value within a factor of 2 (the 1 sigma width). It is then worth mentioning that a similar value on this limit has been derived in two dark GRB (Djorgovski *et al.* 2001, Piro *et al.* 2002) by modelling the broad band data via the standard fireball model. Both these events have been associated with host galaxies at $z \lesssim 5$, leading to the conclusion that the optical is depleted by dust in star-forming region. Indeed, one of these two objects (GRB000210) is also included in our sample.

This association does not exclude that other optically depleted GRB are indeed at $z \gtrsim 5$. Actually, Bromm & Loeb (2002) have estimated that more than 20-30% of GRB should lie at $z \gtrsim 5$. Indeed, we find that the average X-ray afterglow flux of optically depleted GRB's is 5 times lower than OTGRB's, an effect that can be straightforwardly attributed to distance. We point out, however, that this effect could also be explained in the obscuration scenario, assuming that dark GRB are less collimated than OTGRB's while retaining a similar total energy (Reichart & Yost 2001).

Since most of the redshift of GRB are derived from optical spectra, there is a strong observational bias against high- z GRB. This limitation can be overcome only by X-ray spectroscopy (X-ray redshift) or far infrared measurements.

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